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The evolution of offshore wind power in the United Kingdom

Paraic Higgins *, Aoife Foley

School of Mechanical and Aerospace Engineering, Queen's University Belfast, Ashby Building, Stranmillis Road, Belfast, BT9 5AH, United Kingdom

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ABSTRACT

In the United Kingdom wind power is recognised as the main source of renewable energy to achieve the European Union 2020 renewable energy targets. Currently over 50% of renewable power is generated from onshore wind with a large number of offshore wind projects in development. Recently the government has re-iterated its commitment to offshore wind power and has announced that offshore wind subsidies are to increase from £135/MWh to £140/MWh until 2019. This paper provides a detailed overview of the offshore wind power industry in the United Kingdom in terms of market growth, policy development and offshore wind farm costs. The paper clearly shows that the United Kingdom is the world leader for installed offshore wind power capacity as pro-active policies and procedures have made it the most attractive location to develop offshore wind farm arrays. The key finding is that the United Kingdom has the potential to continue to lead the world in offshore wind power as it has over 48 GW of offshore wind power projects at different stages of operation and development. The growth of offshore wind power in the United Kingdom has seen offshore wind farm costs rise and level off at approximately £3 million/MW, which are higher than onshore wind costs at £1.5–2 million/MW. Considering the recent increase in offshore wind power subsidies and plans for 48 GW of offshore wind power could see more offshore wind power becoming increasingly financially competitive with onshore wind power. Therefore offshore wind power is likely to become a significant source of electricity in the United Kingdom beyond 2020.

Contents

* Corresponding author. Tel.: +44 28 90974569.
E-mail address: phiggins14@qub.ac.uk (P. Higgins).

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1. Introduction

The United Kingdom's (UK) renewable energy strategy stated that 15% of electricity would have to come from renewable sources to achieve the European Union's (EU) 2020 Renewable Energy Directive and tackle climate change [1]. In 2013 offshore wind was identified as the main renewable energy source for achieving the 2020 target [2]. This was a considerable policy change from the early 1990s where the replacement of coal fired generation plants with combined cycle gas turbines resulted in the majority of carbon dioxide emissions reductions in the UK [3]. Over the same period gas production peaked and since 2005 the UK has become a net importer of natural gas [3]. In addition the UK's existing electricity generating plant is approaching the end of its predicted life cycle. It is estimated that some 80% of current thermal plant will need to be replaced by 2030. This includes 8.5 GW of coal power stations closing by 2017 due to the revised large combustion plant directive [4] and 9 GW of nuclear plants [5]. Therefore the 2030 target of 40 GW of offshore wind energy in the UK is critical to achieving National and European renewable electricity targets [2]. A review of published information worldwide indicates offshore generating capacity has increased fourfold from approximately 1.1 GW to 4.9 GW in the last five years. Denmark was the major developer in the early 2000s but it was the UK that has developed the most in the last five years, as shown in Fig. 1.

Although there is nearly 5 GW of offshore wind installed worldwide the industry is still in its infancy stage similar to onshore wind in the 1990s. Throughout the last five years the large equipment manufacturers have invested heavily in offshore wind turbine research and development despite the global economic crisis [6–8]. This private investment has been supported by government policies and feed-in tariffs, particularly in the UK. The development of offshore wind in the UK over the last ten years has seen project costs vary for a number of reasons. Studies have shown costs are linked to increasing water depths and distance from shore [9,10]. Additional driving factors have been identified as rising material costs, commodities and labour costs, and rising cost of offshore turbines due to supply chain constraints [5,11–14]. A key finding of this research is that capital costs for offshore wind turbines appear to be levelling off and the UK is in a strong position to take advantage and achieve their EU 2020 targets.

This paper contains seven sections. Section 1 presents the introduction. Section 2 discusses development status of the UK offshore wind industry from 2000 to 2025. The technology development of offshore wind turbines using published information, data and web sources is covered in Section 3. Section 4 describes the UK market in terms of policy development and national attractiveness. Section 5 discusses UK development costs and financial strategies. Section 6 analyses the impact economies of scale have on the capital costs for offshore wind projects under varying distances to shore and turbine costs. The trend for future capital costs for offshore wind power projects is also analysed. Section 7 discusses the key findings of the paper.

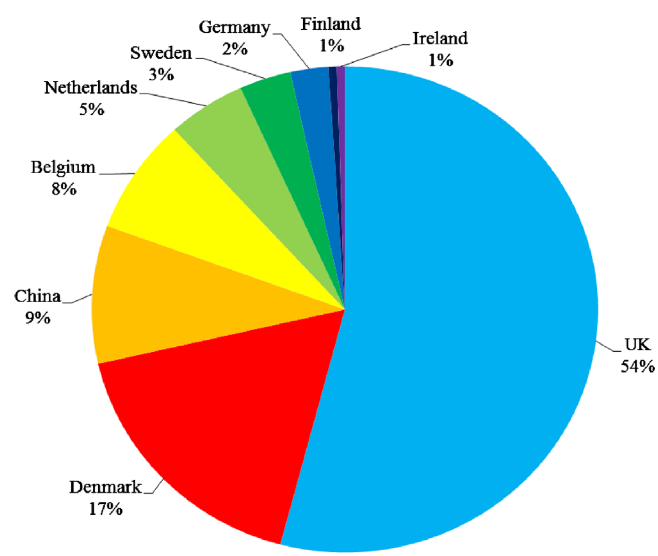
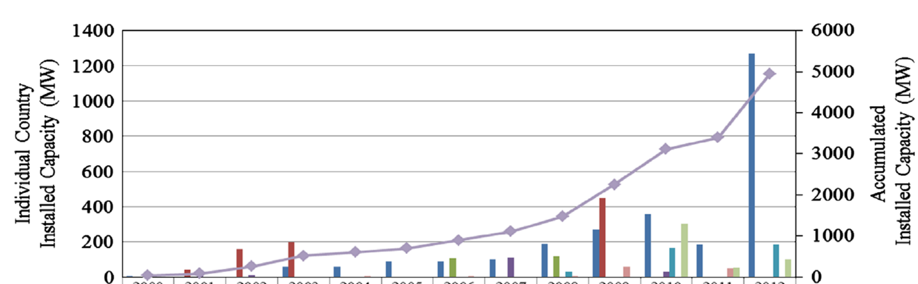


Fig. 2. International breakdown of installed offshore wind capacity.



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
UK	4	0	0	60	60	90	90	100	187	270	357	184	1271
Denmark	0	40	160	200	0	0	0	0	0	448	0	0	0
Netherlands	0	0	0	0	0	0	108	0	120	0	0	0	0
Sweden	0	11	10	0	0	0	0	110	0	0	30	0	0
Belgium	0	0	0	0	0	0	0	0	30	0	165	0	185
Germany	0	0	0	0	5	0	3	0	5	60	0	48	0
China	0	0	0	0	0	0	0	0	0	0	303	51.5	99.3
Accumulated (MW)	36	87	257	517	607	697	898	1108	1475	2252.8	3109.7	3393.1	4947.7

Installation Year

Fig. 1. Worldwide installed offshore wind capacity (2000–2012).

2. Market development

2.1. Offshore wind in the UK: 2000–2014

Fig. 2 presents the world offshore wind generating capacity at the end of 2013 and shows that over 50% is attributed to the UK. In the last few years the UK has over taken Denmark in offshore wind generating capacity as the offshore wind farm projects from the Crown Estate's round 1 and the majority of round 2 have been fully commissioned.

The development of offshore wind in the UK has been created in three rounds (i.e. calls for proposals) which have been defined by the Crown Estate. The Crown Estate manages property owned by the English monarch and has a commercial mandate to optimise returns from their assets. The Crown Estate assets consist of urban and rural areas, and around half of the foreshore and almost the entire seabed around the UK [15]. In the early 2000s the UK's Department of Trade and Industry launched the 'Offshore Wind Capital Grants Scheme' to promote the deployment of offshore wind. The scheme was to provide valuable experience for the offshore wind projects in rounds 2 and 3 [16]. Round 1 commenced in 2000 with the Blyth offshore wind farm and all twelve projects (1191 MW) have been fully installed with the last offshore wind farm, Ormonde, fully operational in early 2012. The leasing for round 2 commenced in 2003 with the first offshore wind farm operational in 2010, the Walney Phase 1. Round 2 consists of seventeen offshore wind projects with a generating capacity of 7.2 GW. At the end of 2013 there are eight projects operational with a generating capacity of 2.45 GW, five projects (1.5 GW) in construction and eight projects (3.25 GW) in planning. In 2009 the leasing for the round 3 projects commenced with over 36 GW of offshore wind capacity identified in UK waters [17]. At the end of 2013 five projects with an installed capacity of 3.4 GW were already in the planning stage.

Up until 2007, offshore wind farms were being developed in lesser challenging environments close to shore and at depths less than 20 m. The Beatrice wind farm was the first of its kind in a water depth of 40 m and at a distance of 25 km from shore. The objective of the Beatrice wind farm was to develop the technology for the first deep-water wind farm and to determine if large scale developments of this turbine type were viable. Table 1 shows that since the commissioning of the Beatrice wind farm only one wind farm has been developed in the UK with a distance greater than 25 km from shore, namely the Greater Gabbard project. The capacity of offshore wind farms have been gradually increasing and in 2013 the London array offshore wind farm was fully commissioned, making it the largest offshore wind farm in the world with an installed capacity of 630 MW.

It is estimated that 4000 people are currently employed in the offshore wind power industry. Approximately 25% of these are involved in the operation and maintenance of the existing offshore wind farms and ports throughout the UK [19]. The UK government have identified the development of the operation and maintenance and supply chain as key elements to their offshore wind industrial strategy [2]. Currently in the UK there are a number of production and assembly facilities for turbine components. Nacelle assembly facilities are provided by GAMESA, AREVA, Samsung and Siemens, blade production facilities are provided by AREVA and GAMESA, turbine foundations are provided by TAG, Burntisland and Fabrications (BiFab) and Offshore Group Newcastle (OGN); however, tower production is not available in the UK and must be imported [20]. There has been significant investment in the UK but 'much larger opportunities remain as the majority of components and services are still being supplied from the continent' [20].

2.2. Offshore wind in the UK: 2014–2025

The UK's system operator (National Grid) produced a report on the 'UK future energy scenarios' which included two renewable energy scenarios, 'slow progression' and 'gone green'. Under the 'slow progression' scenario the renewable energy target for 2020 is not met but the carbon reduction is achieved. Under the 'gone green' scenario the 2020 renewable energy and the greenhouse gas emissions are achieved. The 'slow progression' scenario requires 15.9 GW of installed offshore wind power by 2025 while the 'gone green' scenario requires 37.5 GW of installed offshore wind power by 2025. However, the combined installed capacity of

Table 1
List of UK commissioned offshore wind farms (2000–2014).
Source: [18].

Year of installation	Project	Capacity (MW)	Total capacity (MW)	Max water depth (m)	Max distance to shore (km)	Wind turbine manufacturer	Crown estate round
2000	Blyth	3.8	4	6	1	Vestas	1
2003	North Hoyle	60	64	12	7.5	Vestas	1
2004	Scroby sands	60	124	10	3	Vestas	1
2005	Kentish flats	90	214	5	8.5	Vestas	1
2006	Barrow	90	304	15	7	Vestas	1
2007	Beatrice	10	314	40	25	REpower	1
2007	Burbo Bank	90	404	10	5.2	Siemens	1
2008	Inner Dowsing	97.2	501	10	5.2	Siemens	1
2008	Lynn	97	598	10	5.2	Siemens	1
2009	Rhyl Flats	90	688	8	8	Siemens	1
2009	Robin Rigg	180	868	5	9.5	Vestas	1
2010	Gunfleet Sands	173	1041	8	7	Siemens	1
2010	Walney Phase 1	183.6	1225	23	14	Siemens	2
2011	Walney Phase 2	183.6	1408	30	14	Siemens	2
2012	Greater Gabbard	504	1912	32	36	Siemens	2
2012	Ormonde	150	2062	21	9.5	REpower	1
2012	Thanet	300	2362	23	12	Vestas	2
2012	London Array 1	630	2992	25	20	Siemens	2
2012	Sheringham Shoal	316.8	3309	23	23	Siemens	2
2013	Lincs	270	3579	15	8	Siemens	2
2013	Teeside	62.1	3641	18	2.2	Siemens	2
	Total	3641					

the Crown Estate's offshore wind Round 1, 2 and 3 plans are greater than 40 GW. The full development of the Round 3 projects alone by 2025 should see the UK reach the 2025 renewable target [2].

Fig. 3 illustrates that the majority of offshore wind farm projects that are operational or have consent are located at water depths of between 20 m and 40 m and at distances of 20 km to 40 km from shore. The bubble size in Fig. 3 represents the installed generation capacity of each wind farm. The majority of round 3 offshore wind farms in planning are at sites with water depths between 20 m and 50 m and distances to shore of no greater than 60 km. This is due to the round 3 offshore energy strategic environmental assessment that excluded the Scottish Renewable Energy Zone and Northern Irish waters within the twelve nautical mile territorial sea limit and all waters in England and Wales with water depths greater than 60 m [17]. The 13 GW Dogger Bank project is the largest round 3 project and is currently the world's largest planned offshore wind farm. The Dogger Bank project consortium consists of some of the leading offshore wind developers including Scottish and Southern Energy (SSE), RWE, Statoil and Statkraft [21].

If the round 3 offshore wind farm plans are achieved then the UK will remain as the dominant global player in the offshore wind industry. Although Denmark could be referred to as the first market mover in offshore wind power technology development, the UK can now be called the first market mover in the securing offshore wind project financing. This is significant because by being the first to significantly develop offshore wind farm projects, the UK gained the advantage of having reduced competition when attracting investment from European investors, banks and the supply chain [22].

It is estimated that the offshore wind industry could support 30,000 to 40,000 jobs by 2020 with a gross value added to the UK economy of £7 billion if proactive manufacturing strategies are implemented by 2020 [2,23]. The employment breakdown in the offshore wind power industry in 2020 could be 55% for services (financial and legal), 20% for installation and operation and maintenance, 17.5% for turbine and component manufacturing, and 7.5% for engineering and design. The UK government has identified a potential further 30,000 jobs if proactive manufacturing strategies are implemented by 2020 [23]. These strategies include providing research and development funding, testing and demonstration facilities, and land and funding for new factories and port infrastructure. The offshore wind power targets for 2020 require significant improvements to the supply chain. An increase in manufacturing capacity is required if the 2020 targets are to be achieved as the UK currently has 40% of the facilities required to achieve the 2020 targets are operational [20].

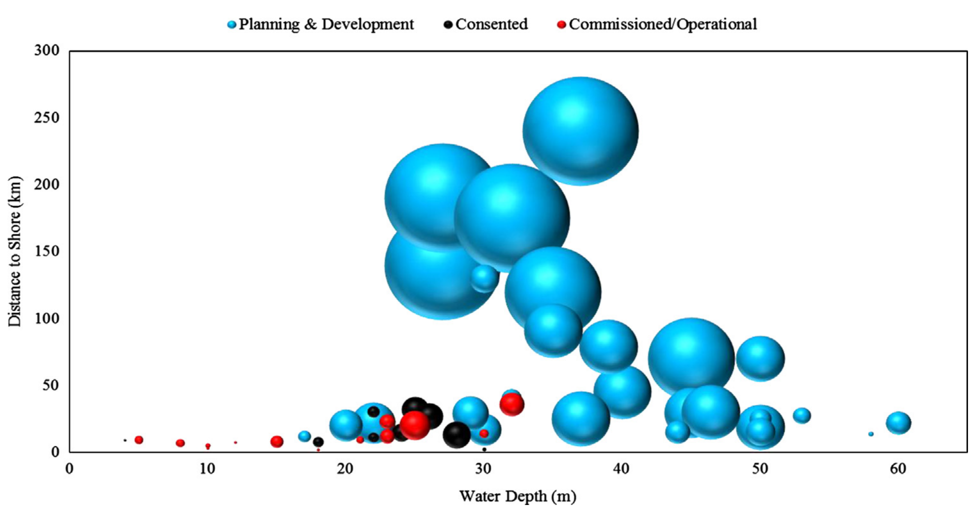


Fig. 3. Distance to shore and water depth of current and future offshore wind projects.

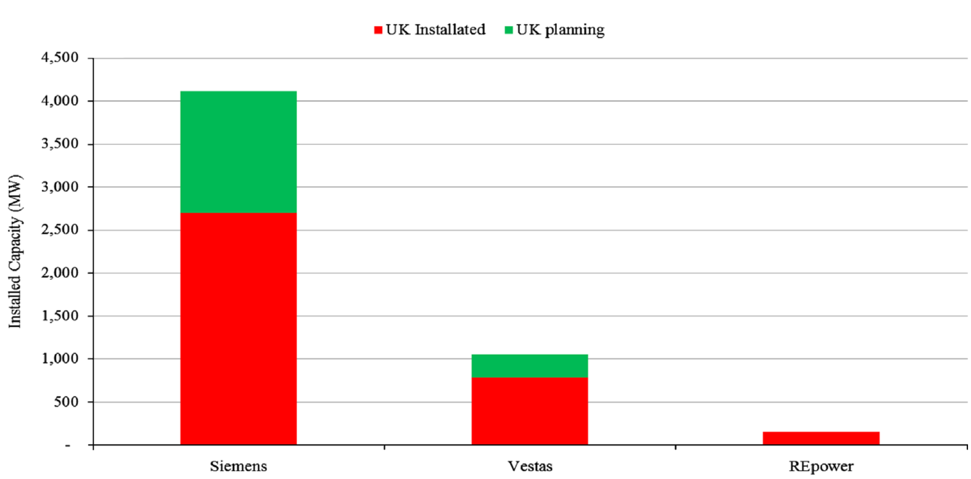


Fig. 4. UK installed and in planning offshore wind capacity per manufacturer.

3. Technology development

Even though the onshore wind industry is viewed as a mature technology amongst renewable technologies, offshore wind is still in the early stages of development and deployment. The United States of America (USA) National Renewable Energy Laboratory (NREL) perceives the similarities of both onshore and offshore wind power to diminish as the different characteristics in environment, market and infrastructure will force the development path of offshore wind turbines to diverge from onshore turbines [24]. The ability to transfer knowledge from the onshore wind research and development into the offshore wind industry has helped reduce time and costs associated with offshore wind turbines. The complexity of converting onshore wind turbine technology to the offshore environment resulted in a limited number of wind turbine manufacturers progressing into the offshore industry. Siemens and Vestas led the way in terms of worldwide installed capacity and up to the start of 2012 they had the only offshore turbines installed in the UK. Since then REpower has commissioned 150 MW in the Ormonde wind farm. Fig. 4 illustrates the significant market share Siemens and Vestas have of the installed and future offshore wind power in the UK.

Even though there is a modest number of worldwide offshore wind turbine manufacturers most of the turbine designs consist of the same components. The five most expensive components of a 5 MW offshore wind turbine are the foundation, tower, blades, drive train and substation [25,26].

3.1. Foundations

The majority of operational/commissioned offshore wind farms in the UK are at water depths of less than 30 m. The next logical step is to continue developing further from shore and at deeper sites [9]. The deployment of offshore wind turbines further from shore and at deeper sites requires different foundations [23]. The five different foundations are monopile, gravity, tripod, jacket and floating. Fig. 5 displays all five types of offshore wind foundations.

Monopile foundations account for 96% of the commissioned offshore wind turbine foundations and the remaining 4% are jacket foundations. Out of the 3.3 GW of offshore wind projects that will be developed in the next five years Fife Energy Park (7 MW) and 2-B Energy Test site (12 MW) are the only projects without monopile foundations. Both offshore wind projects will install jacket foundations. Table 2 illustrates the different foundations, the associated water depths and wind farm examples.

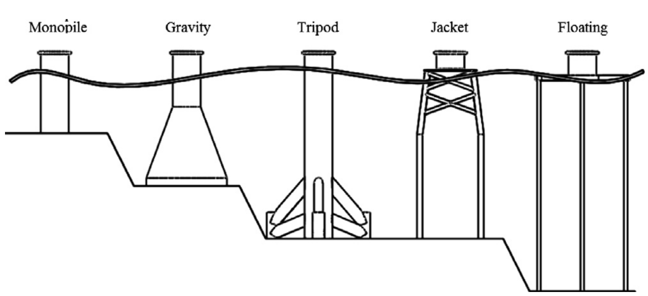


Fig. 5. Offshore wind turbine foundations.

A monopile foundation is limited to approximately 30 m water depths for design reasons. The natural frequency of a monopile decreases with installed water depth and at a certain depth it will become excited by the rotor speed and blade pass. For larger water depths the diameter of the monopile and thickness must increase to preserve stiffness; thus the volumetric mass, material cost and installation equipment all increase. At approximately 30 m water depth, the installation equipment is no longer practical and the monopile designs are limited structurally [24]. Gravity based foundations have less structural limits than monopiles, but their costs increase rapidly with water depth [24]. At water depths greater than 30 m, tripod and jacket foundations are usually deployed as they provide a wider substructure base which is better suited to neutralising the overturning forces [24] and have less reaction to wave resonance [27]. In 2009 the first full scale floating wind turbine was installed at a water depth of 220 m by Statoil off the coast of Norway [28]. There are a number of other floating turbines in testing worldwide including the Windfloat Floater in the USA, Blue high tension leg platform (TLP) in the Netherlands, Poseidon Floating Power in Denmark and Mitsui TLP in Japan [29,30]. The UK's Energy Technology Institute (ETI) is currently investigating the feasibility of a floating offshore wind turbine foundation which will be deployed in wave hub in the south west of England [30].

3.2. Towers

Over time the offshore wind turbine tower design has evolved to include specialist coating materials to withstand the corrosiveness of seawater and increased strength characteristics due to additional loading. The rate of corrosion of offshore wind turbines has been shown to be far greater than that of onshore wind turbines and as a result a number of EU standards have been established for the corrosion protection of offshore structures [31]. A typical offshore wind turbine tower corrosion protection consists of two or three of specialized epoxy coatings with a polyurethane top coat [31,32]. The corrosion rate of the steel tower varies according to the water level. Below the seawater level a corrosion rate of 0.2 mm/year is experienced, however the splash zone (about seawater level) experiences a corrosion rate of 0.4 mm/year [32]. The thickness of each coating depends on the area of the tower and the water level i.e. the splash zones requires a thicker coating.

A typical 4 MW turbine tower diameter is between 3 m and 5 m, a 6 MW turbine tower diameter would be between 5 m and 7 m [33] and potentially up to 9 m for a 20 MW turbine [34]. The towers are built from tapered tubular steel sections and welded together in lengths of 30 m to 40 m, and transported to site for assembly. This process is utilised as shipping transport restrictions limit the tower sections lengths. As more manufacturers develop port assembly and manufacturing facilities the possibility of

Table 2
Foundation designs.
Source: authors' calculation based on [18].

	Monopile	Gravity base	Tripod	Jacket	Floating
Depth (m)	0–30 m	0–40 m	0–50 m	0–50 m	> 60 m
Wind farm	Thanet, UK Baltic, Germany Belwind, Belgium	Rodsand, Denmark Sprogo, Denmark Lillgrund, Sweden	Hooksiel, Germany Alpha Ventus, Germany	Thornton Bank Phase 2, Belgium Ormonde UK Beatrice, UK	Hywind, Norway

manufacturing single section towers can be achieved [35,36]. A single section length will result in cost improvements as it would remove the need for multiple tower lifts and reduce the need for numerous assembly connections [33]. Transportation issues will arise as increments in wind turbine capacities result in taller and stronger towers to deal with heavier nacelles. The transportation and installation for a range of offshore wind turbines has been analysed and it has been shown that vessel capacity is steadily increasing [37]. In 2003 the average vessel capacity was 1500 m^2 and by 2014 it will be 3500 m^2. The Greater Gabbard project involved two vessels the Leviathan and the Seajack each with a deck capacity of 900 m^2 and 2500 m^2, respectively. The Leviathan transported two 3.6 MW turbines and the Seajack transported three 3.6 MW turbines. The research concluded vessel capacity to be the 'main parameter determining the transportation efficiency' [37].

The taller the onshore turbine the greater the experienced wind speed, however, the wind shear offshore is lower than onshore due to different surface characteristics. Therefore offshore wind turbine towers can be shorter as less height is required to achieve comparable wind speeds [38]. A key consideration in determining tower heights in the UK is the Maritime and Coastguard Agency guideline requirement of a minimum height of 22 m between the lowest point of the rotor sweep and the mean high water springs [39]. This clearance is for small craft. The wind shear and Maritime and Coastguard Agency minimum height mean there is little benefit to increasing the rotor sweep heights above the combination of the blade radius and the 22 m requirement [33]. Fig. 6 illustrates the offshore tower height restrictions.

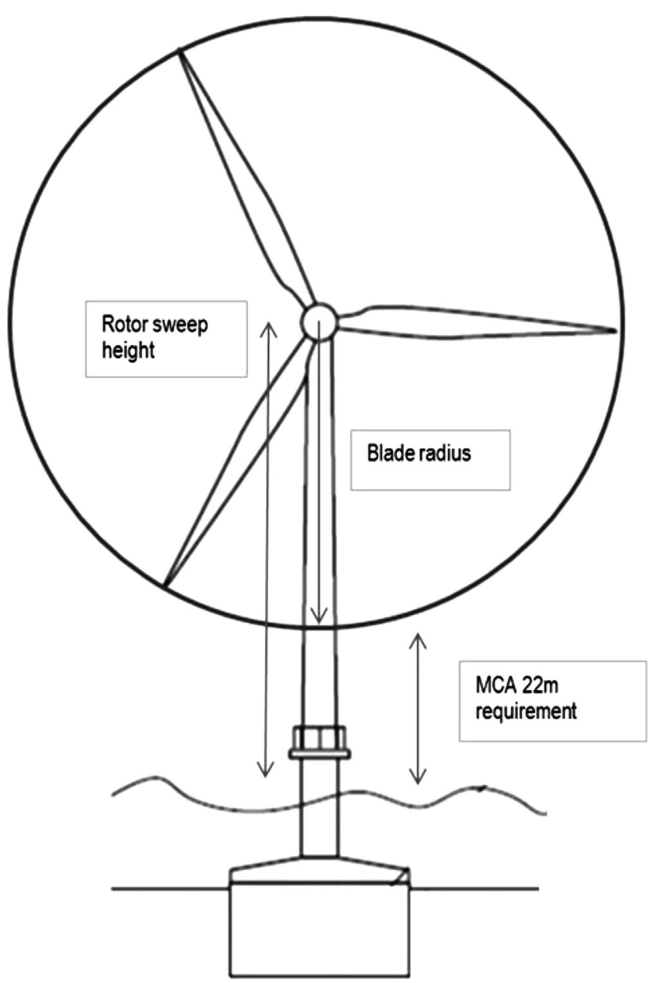


Fig. 6. UK tower height restrictions.

As expected, an analysis of offshore wind farms deployed in UK waters shows a close correlation between the increase in generation capacity of the wind turbine and the tower height. The first offshore wind turbine deployed in the UK was the Vestas V66-2 MW offshore wind turbine deployed in the Blyth offshore wind farm in the early 2000s. The Vestas V66-2 MW had a tower height of 60 m and a max generation capacity of 2 MW. Currently the largest turbine installed in the UK is the REpower 5 M in the Ormonde offshore wind farm with a max height and generating capacity of 95 m and 5 MW, respectively.

3.3. Blades

The rotor diameter of offshore wind turbines have steadily increased from the Vestas V66-2 MW diameter of 66 m to the Siemens SWT-3.6-120 diameter of 120 m in 2013. The offshore wind turbine with the largest rotor diameter in planning is the Samsung Heavy Industries S7.0–171 to be deployed in the Fife Energy Park with a rotor diameter of 171.2 m [40]. A report on the cost breakdown of a 5 MW turbine determined the blades as the largest component cost [25]. Manufacturing and assembly is a key process in the blade life cycle as 30% of blade costs are in the manufacturing process [33]. The current techniques are continuously evolving with new products and materials being developed to dramatically reduce the costs. Of the top three manufactures Siemens and Vestas manufacture the blades in house and REpower purchases from LM Wind Power [33]. All three manufacturers use either carbon fibre or glass fibre in the construction of their blades [33]. The latest materials that are being developed are self-healing composites and nano-fillers. The self-healing composites could extend the life cycle of the blades due to their 'self-slow crack development'. The nano-fillers could increase the stiffness and fatigue characteristics of blades resulting in longer life [33]. Unlike Siemens, Vestas and REpower, General Electric (GE) is investigating a new generation of lighter blade, which will be quicker to fabricate than existing fibreglass blades. The blade will consist of a metal space frame enclosed by architectural fabrics. The length of the blade will consist of ribs with the fabric tensioned around them. This new method will allow the design of the blades to exceed 120 m. This will reduce the problem with manufacturing and transport as the blades can be built and assembled on site. General Electric estimates a reduction of 25% to 40% in blade costs due to the new design [6]. Other than blade materials and manufacturing processes, research indicates as the generating capacity increases the industry expects an increase in blade size and improvements in blade aerodynamics. A potential future improvement is increased rotor tip speed to improve energy capture and reduce torque. The disadvantages of increased tip speed are increased fatigue loading, increased blade erosion and reduced blade performance due to aerodynamic uncertainties [33].

Even though the onshore wind industry appears to have converged on a three bladed turbine there are still technology companies developing new concepts such as a 2-B Energy which is developing a two bladed offshore wind turbine. 2-B energy was awarded an offshore test site for their 6 MW turbine 20 m of the coast of Methil in the UK [41].

3.4. Drivetrain

The most commonly deployed offshore wind turbines in the UK are the Siemens SWT-3.6-107 and SWT-3.6-120 with 68% of the total number of installed offshore wind turbines. Both of these turbines have the same 3.6 MW asynchronous generators and transmission system. As shown in Fig. 4 the other major offshore wind turbine manufacturer is Vestas. All 280 Vestas offshore wind turbines installed in the UK have high speed doubly-fed induction

generators (DFIG) as part of their drivetrain. A Fraunhofer Institute report highlighted that DFIG and asynchronous generators are most commonly used in German offshore wind turbines but the number of direct drive wind turbines is increasing [42]. The same can be seen in the UK as the next five years will see Siemens and Vestas installing over 2000 offshore wind turbines (SWT-6.0-154 and V112-3.0 MW) with synchronous direct drive permanent magnet generators. This will result in a 50% split of installed asynchronous and synchronous generators. The reason for a change in generators could be the same as the NREL views, that direct drive generators are more reliable than the high speed DFIG gear-driven systems [24]. The key advantage of DFIG systems is that they are lighter than direct drive systems. However, a study showed over 25% of wind turbine downtime is a result of gearbox failure and 5% is generator failure [33]. Removal of the gearbox from the drive train could reduce downtime and project costs [33]. The downside to direct drive generators is the large quantity of copper required and increased manufacturing complexity [33].

The offshore wind industry does not appear to have converged on a preferred drivetrain choice with a number of designs still being developed. The UK's Department of Energy and Climate Change (DECC) through their offshore wind energy technology program have awarded a number of projects funding to improve the performance of offshore wind turbines. David Brown Gear Systems received £1.2 million to develop South Korea's Samsung Heavy Industries 7 MW offshore wind turbine gearbox which will be tested in Scotland's Fife Energy Park. Another company called NGen Tec is developing its low-mass axial-flux permanent magnet generator with direct-drive and mid-speed applications in conjunction with a funding award from DECC [43]. Research into mid-speed generators is being performed as it may result in the generator and gearbox becoming securely coupled therefore eliminating the need for a high-speed shaft coupling and increasing reliability. Through switching generator speeds, a reduction in capital expenditure should be noticed from the reduction in the number and cost of components [33].

The maximum offshore wind turbine generation capacity commercially available is 6 MW. Some of the major companies and consortiums are developing next generation turbines which will be greater than 10 MW. A 15 MW offshore wind turbine is being developed by Accicon, Alstom Wind and GAMESA in conjunction with the Spanish strategic national technical consortiums (CENIT) who are partially funding the €25 million project. General Electric and AMSC Windtec are individually developing a 10 MW turbine with a direct drive high temperature superconducting (HTS) generator. The HTS generator entails the replacement of the standard copper in the generator with superconducting wire, resulting in an increase in efficiency and reduction in generator mass, approximated to be 50% lower than a permanent magnet generator [33]. The downside is that the process requires the use of more expensive materials, higher manufacturing costs and cooling equipment. This technology is still far from commerciality and is expected to have a small market share by 2020 [7].

3.5. Grid and substation

The original offshore wind farms in the early 2000s were grid connected by 33 kV medium voltage alternating current until wind farms moved further from shore and increased in generation capacity resulting in a greater need for offshore electrical substations. Substations usually include medium and or high voltage transformers, switch gears, electrical generators, batteries and busbar systems to regulate voltage flows to the grid. The Crown Estate estimates that a single offshore substation can cost up to £50 million [44]. The UK's first offshore substation was installed at Barrow wind farm in 2006, 7 km from the Cumbrian coast. This substation was constructed by Centrica and DONG [45]. Since then the majority of offshore wind farms developed in the UK have had one or two substations. A report by Siemens found their larger UK offshore wind farms had two substations installed as they helped in reducing the length of inter array cabling [46]. For offshore wind farms with a generating capacity of less than 300 MW a single substation was installed. Bresesti et al. [47] showed that 90 km to shore is the point at which high voltage direct current (HVDC) grid connection costs are cheaper than high voltage alternating current for a 100 MW offshore wind farm. The high voltage cables are the most expensive component of high voltage alternating current connections while the substations are the largest cost for the HVDC connections. The reduction of costs for the larger round 3 offshore wind farms, greater than 1000 MW, will entail minimising the number of offshore substations, HV connections, lengths and losses of inter array cables [47]. These large generating capacity round 3 offshore wind farms will require a number of HVDC connections to ensure security of supply in case of loss of one connection. A further 36 GW of offshore wind projects planned in the UK signals a major challenge to upgrade the grid to integrate this variable renewable source of energy [2]. It is estimated that grid upgrades and extension costs are in the region of £6.1 billion even with relaxed constraints [2].

4. Policy development

It was found that in the early stages of Denmark's offshore wind industry the policy makers established that the most successful method to develop the technology was to promote 'learning by interacting between knowledge institutes, component suppliers, project operators and turbine manufacturers' [48,49]. They discovered the most dominant forms of learning were learning by doing and learning by using. Learning by doing can be classified as the learning that occurs during the technology production. Learning by using is the user knowledge gained through the utilisation of a product. The Danish policies were extremely successful because they were pro-active. The Danish Energy Authority (DEA) anticipated barriers and set about removing them and developed an attractive environment for technology learning. The DEA did this by reducing non-technical risks through a number of policies. First, 'utilities were allowed to pass on the additional costs of producing offshore wind electricity onto the end user' and therefore reduce market risks. Then grid connection costs were covered by the grid operator and not passed onto the project developer. A one-stop shop to reduce regulatory risks was developed. Subsidies were provided for learning and experimenting on small scale offshore wind farms such as Samso of the east coast of Denmark. The DEA ensured data for research purpose was available through its tender conditions. Confidential data had to be available to the Technical University of Denmark (DTU) to perform academic research [48].

The same study found UK policies took a different approach by creating active policies that provided stable conditions for learning only. The electricity market liberalisation forced utilities to cut costs. As a result expensive renewables were seen as risky investments and were not further developed. Offshore wind generation faced subsidy problems as there was only a 'generic renewable energy stimulation mechanism'. In 2003 the renewable obligation was introduced with a future offshore policy programme. This new policy created a more encouraging subsidy regime for offshore wind generation [48]. Both Danish and UK authorities created stable incentive mechanisms that lasted for many years. The policies made the industry 'feel confident that current investments would pay back and therefore the industry felt comfortable in learning by doing and learning by using'. The establishment of stable and long-term policy regimes is fundamental

to the stimulation of technology learning [48]. In the early 2000s the UK government provided an offshore wind capital grant scheme to help advance the early developments of the Crown Estate's round 1 and 2 projects. The scheme consisted of £117 million of funding grants. Ten projects with a combined capacity of approximately 1 GW were funded, North Hoyle, Scroby Sands, Kentish Flats, Barrow, Burbo Bank, Lynn and Inner Dowsing, Robin Rigg, Rhyl Flats and Gunfleet Sands. Through the funding the projects were able to improve the economic feasibility of the project. The impact of the funding saw a cost/MW reduction in the range of £0.111 million/MW to £0.167 million/MW [50–53]. These grants helped to reduce the risk associated with the construction phase and spark industry interest to undertake such projects.

DECC followed the offshore wind capital grant scheme by providing approximately £90 million in funding for offshore wind in the form of two schemes; the offshore wind component technologies development and demonstration scheme (£30 million) and the offshore wind business development scheme which focuses on offshore wind manufacturing at port sites (£60 million). With the correct policies in place the industry has the capabilities to deliver as it did so before in the 90's with the 'dash for gas' and in the last decade with supply chain for onshore wind [23]. DECC is not the only source of funding available to the UK offshore wind sector, the ETI commissions projects in cost, reliability and maintenance of offshore wind. The program aims to increase deployment to 18 GW, reduce electricity costs to be competitive with onshore wind, increase annual farm availability to 97% or 98% and reduce technical uncertainties by 2020. So far the ETI has provided approximately £16 million to number of offshore wind projects [33].

In 2013 the UK government decided to develop a number of electricity market reforms (EMR) to achieve their energy and climate change goals through addressing both security of supply and ensuring sufficient investment in low-carbon technologies while maximising the benefits and minimising costs for consumers and tax payers [54]. The EMR proposes a package of policies consisting of Feed in Tariffs with Contracts for Difference (CfD), Carbon Price Support (CPS) at £30/tCO2 in 2020 [55], Emissions Performance Standard (EPS) and Target Capacity Measures (TCM). A CfD is a long term contract that provides consistent revenue to low carbon generating units such as offshore wind [54]. A CPS is a tax on carbon prices from the emissions trading scheme [54]. The EPS was established to limit emissions from unabated power stations [54]. The TCM were developed to ensure security of supply with the increasing penetration of renewables. It will provide the security through payments for reliable capacity to be available when needed [54]. The UK government re-iterated its commitment to offshore wind power by announcing that offshore wind subsidies are to increase from £135/MWh to £140/MWh until 2019.

The CfD is set to replace the Renewable Obligation Certificate (ROC) mechanism which was created in 2002. The ROC mechanism was introduced to place an obligation on the UK electricity suppliers to provide more of their electricity from renewable sources. At the start of each year electricity suppliers have an annual obligation to supply electricity from renewable generators. Ofgem issues ROCs to renewable electricity generators who then sell them to the suppliers. The electricity suppliers present the ROCs to Ofgem to prove that they have purchased energy from renewable energy sources. The ROCs are tradable commodities and therefore their prices fluctuate. The ROC price at the end of 2013 was approximately £46 [56]. Each renewable energy technology was given different numbers of ROCs to encourage the development of less developed technologies. Onshore wind generators receive 1 ROCs/MWh and offshore wind generators receive 2 ROCs/MWh. The level of support for each band is reviewed every four years [57]. The ROC system has been shown to have not achieved its desired targets [58] and the UK government has decided to introduce a Feed-in-Tariff with CfD to provide a more stable financial support mechanism for renewable generators. The CfD is a long term contract that pays the renewable electricity generator the difference between the market price of electricity and a long term price. The long term price is determined to encourage the investment in a given technology [59]. The UK government expects the CfD to limit the renewable generators' exposure to electricity price volatility, reduce the financial risk to renewable electricity projects and therefore encourage investment in renewable electricity generation. However, Toke [60] believes for generators with a capacity of less than 100 MW the CfD feed-in tariff will not be as 'generous' as the ROC mechanism and therefore renewable energy development might be stunted. Such generators are unlikely to be trading on the electricity market and therefore must request power purchase agreements with energy suppliers. The energy suppliers are likely to charge the balancing risk to the generator and as result the generator receives less than the CfD [60]. This should not be an issue for the future development of offshore wind power as the majority of planned wind farms are being deployed by companies who trade in the UK electricity market. The ROC support mechanism will seize to be offered from the 31st of March 2017 and the implementation of CfDs will commence.

It is suggested that policy makers can affect the cost and profitability of an offshore wind project in many ways [61]. In France, the UK, Ireland and Sweden the project developer is required to supply the grid connection, while in Denmark and Germany the transmission system operator (TSO) supplies the grid connection [45]. If the project developer is responsible for the grid connection, the costs are allocated to the investment costs of the project. However, if the TSO is responsible, the costs are excluded from the project costs. Therefore energy policy makers can have a direct impact on the capital costs of an offshore wind project [61]. The policy makers can also affect offshore wind projects through financial support schemes (e.g. Feed in tariffs or green certificates), total remuneration levels, regulatory framework and the geographic conditions (water depth and distances to shore) of offshore wind zones [61]. A government's ability to affect the profitability of an offshore wind farm through changes to the electricity markets directly impacts the wholesale cost of electricity therefore any changes to the electricity markets requires careful consideration.

The governments of Scotland, Northern Ireland and the Republic of Ireland commissioned a study on the feasibility of an offshore interconnected electricity grid using ocean based renewable resources (i.e. wind, wave and tidal) called the an Irish-Scottish Links on Energy Study (ISLES) in 2012. The ISLES study zone stretched from the west coast of the Isle of Lewis down to the north coast of Northern Ireland and further south into the Irish Sea along the east coast of Ireland [62]. The ISLES zone is estimated to have an offshore wind and combined wave and tidal resource of 12.1 GW and 4.0 GW, respectively. Two projects were identified to 'match technology-ready resource potential with available onshore transmission network capacity' [62]. The two projects identified were referred to as the Northern ISLES and Southern ISLES zones. The Northern ISLES zone is from the south west coast of Scotland down to the north coast of Northern Ireland and north coast of county Donegal in the Republic of Ireland. The zone has a potential 2.1 GW of offshore wind generation capacity and can provide an interconnection capacity between both islands of 2.8 GW. The Southern ISLES zone is along the east coast of Ireland from county Louth to county Wexford. This zone will have a shared offshore wind generation capacity of 3.4 GW with the Republic of Ireland and the UK and an interconnector capacity of 2 GW. The total investment cost for both projects is expected to be £5.6 billion. The ISLES study concluded the development of the

project would provide the UK with an increase of imports in the form of renewable generation from the Irish market and improve the interconnector capacity between both markets.

At a continental level, the EU has enforced legislation on the European electricity and gas markets called the “Third Package”. The aim of the Third Package is to further liberalise European energy markets by 2014 to provide an integrated European electricity market. The Agency for Cooperation of Energy Regulators (ACER) was setup in 2011 to further progress the completion of the internal energy market for both electricity and natural gas by ensuring that market integration and harmonisation of regulatory frameworks are done in respect of the EU's energy policy objectives [63]. Its mission is to support the National Regulatory Authorities (NRAs) in coordinating the Electrical Regional Initiatives (ERIs). One of the ERIs is the France-UK-Ireland (FUI) region which consists of the Single Electricity Market of the Republic of Ireland and Northern Ireland (SEM), the British Electricity Transmission and Trading Agreement (BETTA) market in Great Britain and the French electricity market. The FUI region roadmap was submitted to the European Commission and ACER in July 2011 and is expected to be completed in 2014. The roadmap entails the implementation of the Capacity Allocation and Congestion Management Framework Guidelines (CACM FG) target model and available interconnection capacity [64]. The CACM FG have four priority projects [65]: the single European Price Coupling which aims at optimising the use of existing day-ahead cross border capacities at European level, reducing the day ahead price volatility and improving confidence in organised price references; the Single European Continuous Implicit Mechanism for cross-border intraday trades required to facilitate balancing before the closure of the market and short-term arbitrage; the European Allocation Platform to ensure one single point of contact for the allocation of harmonised long-term transmission rights across Europe; and the Flow Based Allocation Method for short-term capacity allocation for improving network security and the level of capacity made available to the market. The recent completion of the east-west interconnector between the Republic of Ireland and Wales has provided the necessary interconnection between the SEM, BETTA and French electricity market.

4.1. National attractiveness, societal perception and environmental opposition

Government and industry are not the only participants in the offshore wind industry. For all of the benefits provided by offshore wind energy its development is most likely to come down to the price of electricity and consumer reactions [3,66]. One of the main misconceptions with offshore wind energy is that offshore sites are problem free alternatives to onshore sites as offshore have fewer restrictions [9,67]. The first offshore wind farms in the UK and elsewhere around the world were not free from opposition, for example, Hagget [68] stated that “turbines, even several miles offshore, still have a visual impact—and for many people, this is a decidedly negative impact”. Not only is public opposition a problem, as in the Firth of Forth, Scotland, it is the fishing industry that is expected to pose a major challenge to the development of offshore wind power projects [69].

A key facet of developing a wind farm is to gauge the public's opinion as they are capable of stalling the development of a wind farm, as seen with the Cape Wind project in the USA. In a European Commission Eurobarometer survey at least 55% of respondents view “increasing the share of renewable energy in the EU by 20% by 2020” and “reducing EU greenhouse gas emissions by at least 20% by 2020 compared to 1990” as credible targets [70]. However, when asked what was the most important issue facing their country the environment, climate and energy issues was amongst the least important. Most significantly rising prices was third on the list and unemployment was second. The wind industry has the capability to not only benefit the environment but also employment, investment, electricity price, research and economic activity [9]. The European Wind Energy Association (EWEA) predict that by 2020 approximately 462,000 will be employed by the offshore wind sector and a total of €66 billion will be invested in the EU [71]. The existence of a supply chain in a country could significantly aid the developed of offshore wind projects, as there would be greater public acceptance of offshore wind farms if the public experience direct economic benefit from employment throughout the whole wind turbine life cycle not just the installation and operation and maintenance [68].

Developing an offshore wind power project is expensive and risky under current market conditions. Most investors review each country to assess which is the most suitable and profitable. Two of the big four professional services companies in the world, Ernst and Young and KPMG, produced reports ranking countries in terms of their attractiveness [22,72]. Ernst and Young index assessed power take-off, tax climate, grant or soft learning availability, market growth potential, current installed base, resources quality and project size. KPMG assessed the financial attractiveness of the individual countries by surveying industry participants for the offshore wind markets in relation to the expected returns. Prassler et al. [61] assessed the European countries by performing an economic analysis of the hypothetical offshore wind projects for a set of scenarios. Table 3 shows the results of all three reports and highlights the UK as the most attractive country for developing offshore wind. The academic study shows even though a country might have all the qualities to make it an attractive for offshore wind, the project success ultimately comes down to the

Table 3
EU country attractiveness to offshore wind.
Source: [22,56,67].

Rank	Ernst & Young	KPMG	T. Prassler & J. Schaechtele
Attractive	United Kingdom	United Kingdom	United Kingdom (Irish Sea)
	Germany	Germany	United Kingdom (North Sea)
	Belgium	Belgium	Belgium
	Denmark	Netherland	Germany (North Sea)
	France	Spain	France (Channel)
	Sweden	Ireland	Denmark
	Netherlands	Denmark	France (Atlantic)
	Ireland	France	Germany (Baltic Sea)
Less attractive		Sweden	United Kingdom (Round III)

individual project due to 'available resource, geographic parameters and responsibility for the grid connection'.

5. Offshore wind power development costs and financial strategies

5.1. Development costs

The capital cost for each offshore wind farm is different due to a variety of reasons such as turbines, foundations and site characteristics. Fig. 7 is a breakdown of capital costs for an offshore wind farm from a selection of sources [73–77]. On average the percentage of capital cost/MW for the turbine is quite similar. The structure and installation and grid connection vary due to the different geographic characteristics (depth and distance) and local country costs of each wind farm site.

The offshore wind farm cost/MW was estimated, some years ago at around €2 million/MW [5]. This cost has increased and presently some offshore wind installations are between €3 million/MW and €4 million/MW [78,79]. Esteban [78] views the industry still in its infancy and still learning from deployment which could explain the increase in cost per installed MW.

The European Environment Agency stated as a site moves to deeper waters or further from shore, the foundation costs of wind turbines tend to increase [10]. Depending on the generating capacity of the turbine, the changes in cost are different. For offshore wind turbines with capacities between 1 MW and 1.5 MW the foundation costs are estimated to increase by 11% from €317,000 at 7 m depth to €352,000 at 16 m depth [9]. At deeper water sites, a change in water depth of 20 m to 35 m would see a 35% cost/MW increase from €458,000 to €620,000 for a 3.6 MW monopile turbine and a 30% increase from €562,000 to €729,000 for a 5 MW monopile turbine [13]. Some [5,11–13] claim increasing water depths and distance from shore have less impact on project costs and that rising material costs, commodities and labour costs, rising cost of offshore turbines due to supply chain constraints, the limited number of manufacturers in the market and the absence of economies of scale due to low market deployment are key drivers. Zwaan et al. [14] went further and stated the cost increasing effects due to commodity prices completely outshadow the effects of scaling and learning. The Crown Estate stated economies of scale have led to a reduction in installation times and over the past ten years the average installation times of 20 to 30 days has decreased to five to ten days [19].

There are many different opinions as to when the cost reductions will occur. The EWEA predict the increases in capital cost to subside to €1.5 million/MW by 2014/2015 [12]. Some [5] expect a gradual fall in costs of offshore wind by the mid-2020s while the UK Energy Research Centre [13] do not foresee any meaningful reductions in the period to 2015 and are cautiously optimistic for reductions in the period to around 2025. The Carbon Trust [23] predict a minimum cost reduction of 20% by 2020 through economies of scale and an 11% reduction if commodity and material prices return to 2003 levels. Whatever the reduction rate maybe the government will play a key role. During 2012 DECC released their offshore wind cost reduction task force report [80] which sets out key actions to cut the cost of generating electricity by over 30% to £100/MWh by 2020. The report lays out twenty nine recommendations across the supply chain, innovation, contracting strategies, planning and consenting, grid and transmission and financing. The recommendations might ease the costs but factors such as rising commodity prices, moving to deeper water sites and further from shore sites are placing upwards pressure on the costs.

5.2. Financial strategies

The competition for project funding is extremely high amongst offshore wind projects [81]. The large offshore wind project developers have limited project finance and are engaged across most of the EU countries. In the past view years the UK government has made the most progress in promoting themselves as the best country to develop offshore wind projects. This is due to their financial schemes, continued political stability and improved supply chain. The round 3 projects are soon to be implemented and this leaves other European projects with a 'limited window of opportunity to secure equity and debt financing' [22]. The largest group of offshore wind project owners in the UK are the international utilities, with 72% [22]. The self-financing capabilities of the large international utilities will come under increasing pressure as sales margins from the electricity market decrease and projects requiring capital funding increase. The large international utilities will also see their capital spread across rebuilding or modernising existing power plants, development of new carbon capture plants, continued oil and gas exploration and increasing competition for offshore wind projects [22]. The large utilities are collaborating in attempt to minimise these problems. DONG, E.ON and Masdar have developed the 630 MW London array [82].

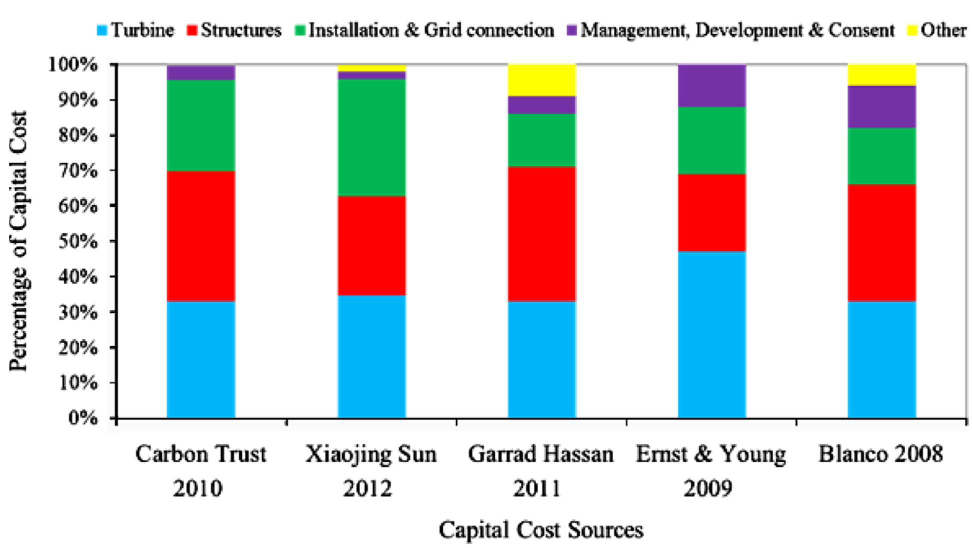


Fig. 7. Capital cost breakdown for offshore wind farms.

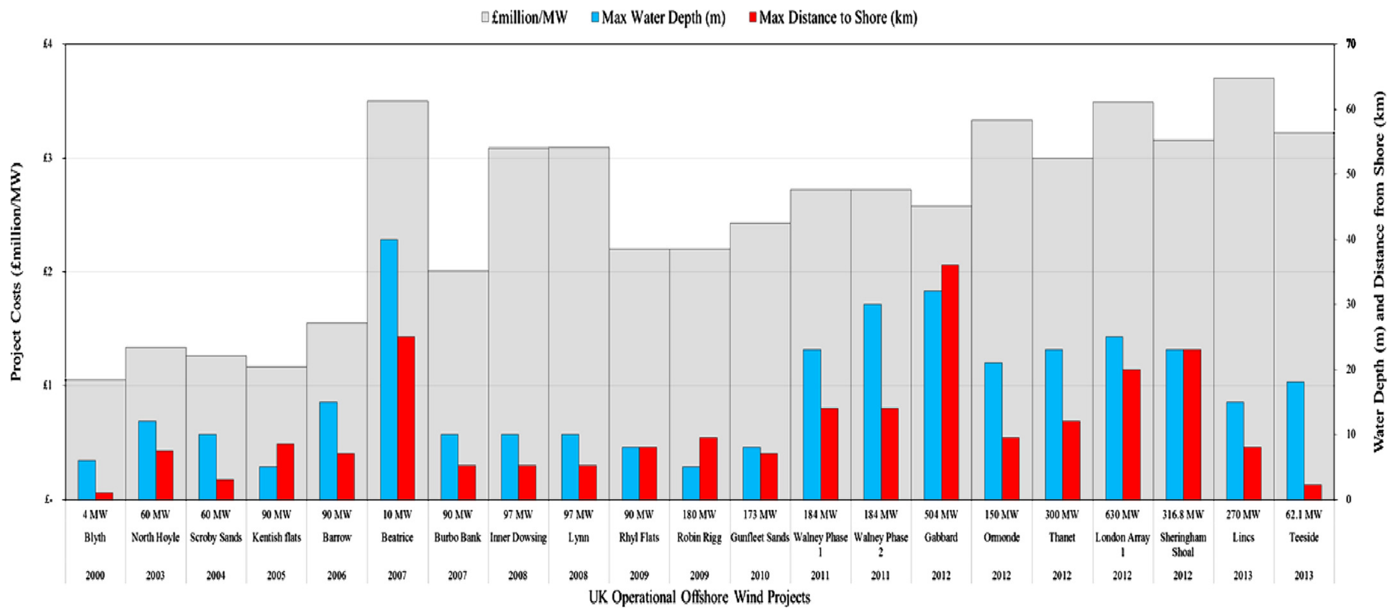


Fig. 8. Project costs for UK operational offshore wind farms (2000–2013).

An industry report suggested the procurement of pre-construction funding to be the most significant barrier to project development [81]. The investment costs at the pre-construction and construction stage are at their highest and revenues are at their lowest. Therefore developers must finance the wind farms through their balance sheets or wait to roll over financing from existing operational farms. The banking sector's failure to provide project finance for the pre-construction phase of an offshore wind farms is due to the perception that it is too high risk [81]. Developers may also face a delay in obtaining the project finance due to the banks requiring an operational track record from existing farms. The now commonly deployed 5 MW wind turbine class was viewed by the banks as a non-proven technology in 2010. It did not qualify for project finance and required support from private investors and public funding [22]. Financial restrictions like these could lead to a loss in the market traction as new technology developments are required to obtain the 2020 targets. The UK government has attempted to solve the funding obstacle by creating a new bank that will provide project finance to green projects only. The UK Green Investment Bank has been launched with a balance of £3 billion of government money to invest in renewable energy, carbon capture and energy efficiency [83].

The significance of project finance was illustrated in the analysis of the North Hoyle and Scroby Sands wind farms [38]. The North Hoyle project received more capital grants and produced more generation year on year than the Scroby Sands project, however the Scroby Sands had a higher net present value as a result of a 3% lower corporate cost of capital for the balance sheet financing. The wind farm projects costs consist of various influences but the 'cost of capital is of paramount importance to derive profit maximisation' [38].

6. Analysis of UK offshore wind project costs

The establishment of trends from project costs must be performed with caution as there could be considerable variability in the costs due to supply chain, technology effects, site characteristics and policy regulations [33,61]. This study removes the policy maker and grid regulation effects by selecting the cost of offshore wind farms in the UK only. Fig. 8 shows the project cost, distance to shore and water depths of UK offshore wind farms from 2000 to 2013 based on data collated from 4C offshore [18]. Water depth, distance to shore, and grid regulation were found to have significant effects on the cost of offshore wind projects [61]. Therefore offshore wind farm cost indicators such as project cost/MW are only meaningful in association with the assumed geographical parameters and grid regulation. The comparison of offshore wind farms developed in the early 2000s with farms developed post 2010 is difficult as project costs have almost tripled, subsidy support has doubled and capital grants are no longer available [38]. The early projects had many flaws in their project costs such as contractors underbid to ensure first mover advantage. This resulted in uncompetitive project costs and consequently some of these contractors became insolvent [38]. Comparisons of early wind farms to present wind farms is unlikely to provide significant trends in the development of offshore wind costs as many factors have changed

Table 4
The impact of distance from shore and number of turbines on project costs/MW. *Source*: authors' calculation based on [85]

Distance (km)	Number of turbines						
	10	15	25	50	100	250	500
5	1	0.938	0.888	0.850	0.831	0.820	0.816
15	1.034	0.960	0.901	0.857	0.835	0.821	0.817
25	1.068	0.983	0.915	0.864	0.838	0.823	0.818
35	1.102	1.006	0.928	0.870	0.842	0.824	0.818
45	1.136	1.028	0.942	0.877	0.845	0.825	0.819
75	1.238	1.096	0.983	0.898	0.855	0.830	0.821
150	1.493	1.266	1.085	0.949	0.881	0.840	0.826

Table 5
The impact of turbine cost and number of turbines on project costs/MW. *Source*: authors' calculation based on [85]

Price of turbine	Number of turbines						
	10	15	25	50	100	250	500
£2000,000	1	0.906	0.831	0.774	0.746	0.729	0.723
£3000,000	1.180	1.086	1.011	0.955	0.926	0.909	0.904
£4000,000	1.361	1.267	1.191	1.135	1.107	1.090	1.084

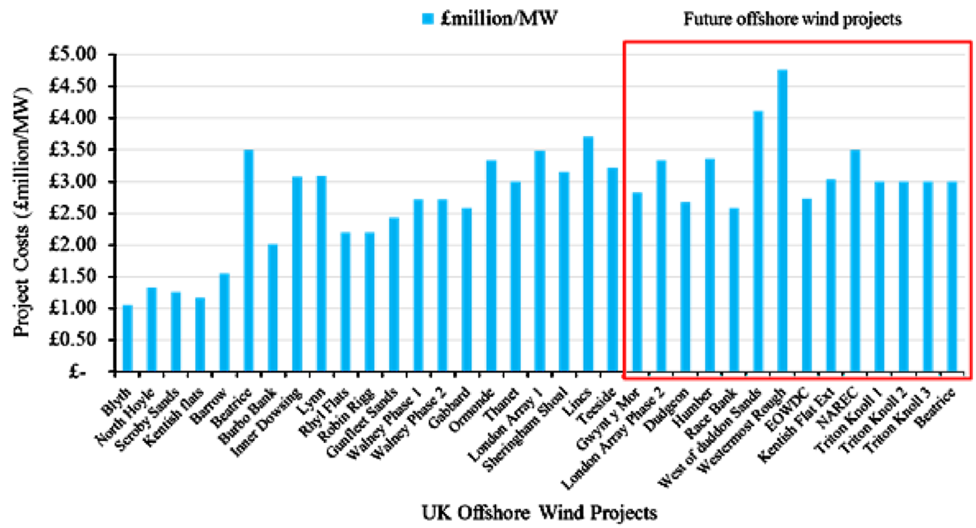


Fig. 9. Project costs for current and future UK offshore shore wind farms (2013 onwards).

therefore making it difficult to examine the effect of individual driving factors.

The impact on projects costs due to a supply chain bottleneck could be assumed to be the same on projects that are developed within the same year. For this study the Walney Phase 1 (2011), Walney Phase 2 (2011) and Greater Gabbard (2012) wind farms were analysed to remove the supply chain affect. Research has shown increases in costs if either water depth or distance to shore increases [9,13,84]. The foundations for the three wind farms are monopile and the installed water depths vary from 15 m to 30 m. The cost impact from water depth variation has been shown to change depending on the distance from shore [84]. A difference of 20 m in water depth and 30 km further from shore could result in a project costs/MW increase of 14% [84]. The Greater Gabbard has a distance to shore twice that of Walney Phase 1 and Walney Phase 2 which should result in a higher project cost; however, the cost is slightly lower. Table 4 illustrates costs increase with distance from shore and decreases with economies of scale. The table highlights the adjustment factor by which project and installation costs should be multiplied for greater distance and economies of scale. Economies of scale require greater turbine numbers at further distances to enable a worthwhile cost reducing effect.

A closer inspection of the projects reveal that Siemens provided the turbines for the three wind farms. Walney Phase 1 consisted of 51 S 3.6 MW and 107 m rotor diameter wind turbines, Walney Phase 2 consisted of 51 S 3.6 MW and 120 m rotor diameter turbines and Greater Gabbard consisted of 140 S 3.6 MW and 107 m rotor diameter turbines. Walney Phase 1 turbine has a 107 m rotor diameter and Walney Phase 2 has a 120 m rotor diameter, a large rotor would increase the cost of each turbine which should increase the project cost. Table 5 illustrates that cost increases with turbine cost and decrease with economies of scale. The effect of turbine price on the overall project cost/MW is far greater than the distance to shore effect. However, the economies of scale can significantly reduce the turbine price effect. Removing Walney Phase 2 from the analysis eliminates the effect of larger turbine costs. The cost difference due to different turbine suppliers can also be removed from this analysis of the Walney Phase 1 and the Greater Gabbard projects.

If both projects were developed by the same owner, Walney Phase 1 (SSE and DONG) and Greater Gabbard (RWE Npower Renewables), it would have been possible to assume the project costs were similar. However, they are not, so it is possible that the stated projects costs consist of different costs. The generating capacity of Greater Gabbard is nearly three times that of Walney Phase 1 and taking into account all of the previous comments it is possible to assume that economies of scale is the main reason for a percentage drop in project costs. More project information is required to fully understand the precise reasons for such a dramatic decrease in project costs.

Future UK offshore wind farms are increasing in turbine numbers and total generating capacity, as seen in Fig. 3. As stated before the comparison of offshore wind farms developed in the early 2000s with those developed post 2010 is difficult as a significant amount of government funding has changed. Fig. 9 illustrates the project costs of the UK offshore winds that are operational, in construction and in advanced planning, based on data collated from 4C offshore [18]. There are many assumptions when analysing the project costs for different wind farms and until specific details for current wind farms are available it will remain difficult to deduce trends.

The purpose of this study is not to validate higher offshore wind project costs but to highlight the trend. It is possible to claim that UK offshore wind farm project costs, in terms of £million/MW, have been steadily rising but there are now signs that they are plateauing around £3 million/MW. This is still considerably higher than projected onshore wind farm costs of £1.5 million/MW to £2 million/MW [86].

7. Discussion and conclusions

Over the last decade the UK government recognised the potential employment and investment benefits from developing offshore wind power and set about implementing pro-active policies and procedures to make the UK the most attractive location to develop offshore wind. Recently the government has re-iterated its commitment to offshore wind power and has announced that offshore wind subsidies are to increase from £135/MWh to £140/MWh until 2019. The policies implemented by the UK government have encouraged large multi-national companies to establish manufacturing bases in the UK and install the majority of global offshore wind energy in the UK. This valuable experience coupled with ambitious 2020 national renewable energy targets and Crown Estate leasing rounds have enabled the UK to remain as one of the most attractive locations to develop future offshore wind farms. It is estimated that the offshore wind industry could support 30,000 to 40,000 jobs in services, manufacturing and

operation and maintenance by 2020 with a gross value added to the UK economy of £7 billion.

The continuing development of offshore wind power has seen wind farm projects being developed further from shore and in deeper waters. Each new wind farm development increases the industry's knowledge and continues to push the boundaries of the technology, installation methods, operation and maintenance methods and financing methods. These developments have resulted in increasing costs, higher than originally expected, however these costs are predicted to fall sometime in the next ten years [5,12,13,23]. The analysis of the developed and future UK offshore wind farms illustrates that the offshore wind turbine costs per MW are showing signs of levelling off at approximately £3 million/MW. This is still significantly higher than onshore wind turbines, however with a further 5 GW to be installed in the next five to ten years the offshore wind farm project costs are expected to decrease further. This decrease in project costs coupled with an increase in offshore wind subsidies should see offshore wind becoming a critical renewable source of electricity in the UK in 2020 and beyond.

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